Formation of a giant HI bridge between M31 and M33 from their tidal interaction

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ABSTRACT

Recent observations have discovered a giant HI bridge that appears to connect between the outer halo regions of M31 and M33. We propose that this HI bridge can be formed as a result of the past interaction between M31 and M33 based on test particle simulations with different orbits of M31 and M33 for the last ~ 9 Gyr. We show that strong tidal interaction between M31 and M33 about $4 - 8$ Gyr ago can strip HI gas from M33 to form HI streams around M31 which can be observed as a HI bridge if they are projected onto the sky. We show that the number fraction of models reproducing well the observed HI distribution of the bridge is only $\sim 0.01\%$ (i.e., ~ 10 among $\sim 10^5$ models) and thus suggest that the observed structure and kinematics of the HI bridge can give some constraints on the past orbits of M31 and M33. We suggest that the observed outer HI warp in M33 could be fossil evidence for the past M31-M33 interaction. We also suggest that some of high velocity clouds (HVCs) recently found in M31 could be HI gas originating from M33. We briefly discuss other possible scenarios for the formation of the HI bridge.

Key words: ISM: clouds – intergalactic medium – radio lines: – galaxies: kinematics and dynamics

1 INTRODUCTION

Recent observational studies on HI gas around M31 based on the Green Bank Telescope (GBT) have reported the presence of at least 20 discrete HI clouds within 50 kpc of the M31 disk (e.g., Thilker et al. 2004). Furthermore possible candidates of HVCs around M31 with heliocentric velocities of -520 to -160 km s^{-1} have been discovered in a blind HI survey for the disk and halo regions of M31 (e.g., Westmeier et al. 2007). Braun & Thilker (2004, hereafter BT04) have discovered a faint bridge-like HI structure that appears to connect between M31 and M33. Although these recent results have provided new clues to formation and evolution of M31 (BT04), no theoretical works have yet clarified the origin of the HI properties surrounding M31, in particular, the intriguing bridge-like structure between M31 and M33.

Corbelli et al. (1989) revealed that the HI gas disk of M33 extends out to twice the optical radius and shows complicated kinematical properties indicative of the presence of a warped disk. By using a tilted ring model, Corbelli & Schneider (1997) demonstrated that the observed distribution and rotation curve profile of HI in the outer part of M33 are consistent with the presence of a warped gas disk.

Although they suggested the formation of the gaseous warp in M33 due to tidal force from M31, the observed unique HI properties of M33 have not been discussed by theoretical and numerical studies in terms of the past M31-M33 interaction.

The purpose of this Letter is to first show that the observed HI bridge between M31 and M33 can be formed from the past tidal interaction between M31 and M33 based on a larger number ($> 10^6$) of test particle simulations for the past interaction. We here try to choose orbital models of M31 and M33 (among a large number of those) which can reproduce well the observed distribution of the HI bridge (BT04). We therefore do not intend to use hydrodynamical and chemodynamical simulations that are numerically costly and were used in our previous studies for the formation of HI streams and bridges around galaxies (e.g., Bekki et al. 2005a, b; 2008).

2 THE MODEL

The present model is two-fold as follows. Firstly we derive the orbital evolution of M31 and M33 in the last 9.2 Gyr for a given set of the present three-dimensional (3D) velocities based on the "backward integration scheme" (Bekki & Chiba

Table 1. The ranges of the simulated present 3D velocities of M31 and M33.

Galaxy name	V_X [a]	V_Y	V_Z
M31	(-148, 286)	(-286, 124)	(-110, 231)
M33	(-165, 214)	(-206, 168)	(-126, 174)

[a] Minimum and maximum velocities adopted in orbital models are shown in units of km s^{-1}.

2005; BC05), in which equation of motion is integrated backward to derive the past orbits of M31 and M33. Then we investigate the dynamical evolution of stellar and gaseous disks of M33 for each of the derived orbits using *test-particle simulations*. In this second step, we investigate whether the spatial distribution of gas particles stripped from M33 due to tidal interaction between M31, M33, and the Galaxy can be consistent with the observed HI distribution by BT04 for each of the orbital models derived in the first step. Throughout this paper, the terms "initial" and "final" mean 9.2 Gyr ago (i.e., the time $T = -9.2$ Gyr) and the present ($T = 0$ Gyr), respectively.

2.1 Orbital evolution

The total masses of M31 (M_{M31}), the Galaxy (M_G), and M33 (M_{M33}) are assumed to be $1.2 \times 10^{12} M_\odot$, $1.9 \times 10^{12} M_\odot$, and $3.8 \times 10^{10} M_\odot$, respectively, which are consistent with observational studies by Evans & Wilkinson (2000), Wilkinson & Evans (1999), and Corbelli & Schneider (1997), respectively. The gravitational potential of the Galaxy Φ_G is assumed to have the logarithmic potential;

$$\Phi_G(r) = -V_0{}^2 \ln r, \qquad (1)$$

where r and V_0 are the distance from the Galactic center and the constant rotational velocity ($= 220$ km s^{-1}), respectively. The logarithmic potential with $V_0 = 250$ km s^{-1} is used for M31. These adopted values for V_0 are consistent with observations (e.g., van den Bergh 2000). For the adopted mass profile for the above potential, the mass of a galaxy within r ($M(r)$) can exceed the adopted total mass of the galaxy at some point. We thus introduce a cut-off radius beyond which $M(r)$ is constant (e.g., $M(r) = M_G$ for the Galaxy). M33 is represented as a point-mass particle with the mass of M_{M33}.

We investigate the 3D orbital evolution of M31 and M33 by adopting the Galactic Cartesian coordinate system used by BC05 in which the Galactic plane is the same as the X-Y plane and the location of the Sun (X, Y, Z) is (-8.5, 0, 0) kpc. The initial distances of M31 and M33 with respect to the center of the Galaxy are set to be 760 kpc and 795 kpc, respectively (van den Bergh 2000). Since the radial velocities (V_r) of M31 and M33 with respect to the Galaxy are observed (van den Bergh 2000), we consider that the following two velocity components are free parameters determining the 3D orbits of M31 and M33: (1) V_θ, where θ is the angle between the Z-axis and the position vector ($\mathbf{r}$) that connects a galaxy (or a particle) and the Galactic center and (2) V_ϕ, where ϕ is the azimuthal angle measured from X-axis to the projection of $\mathbf{r}$ onto the $X - Y$ plane.

For a given set of V_r, we investigate 160000 models with different V_θ and V_ϕ for M31 and M33. Although we have
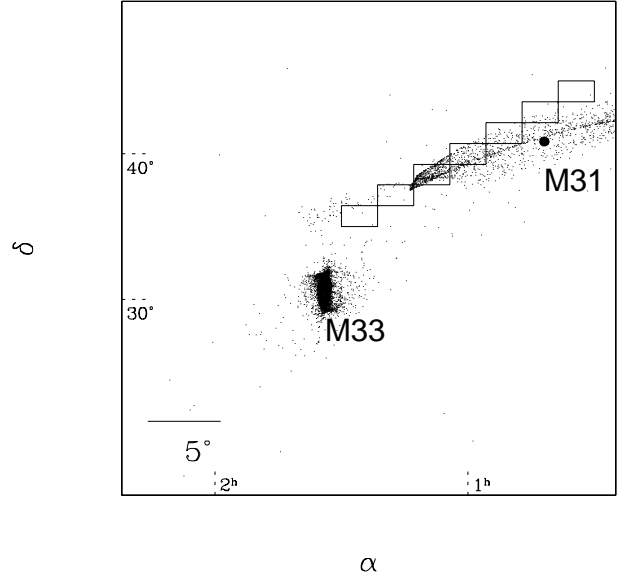

Figure 1. The distribution of gas particles stripped from M33 in the equatorial system (i.e., the α-δ plane) for the model M1. The location of M31 is shown by a filled circle for comparison. The seven rectangular regions shown by solid lines cover the observed location of the HI bridge (BT04). These rectangular regions are used for finding the successful models that can reproduce well the observed distribution of HI gas around M31.
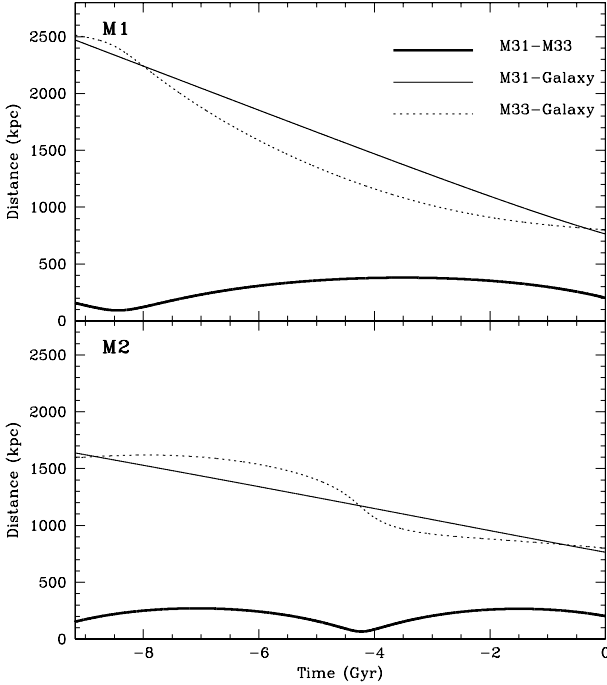
investigated a large number of models ($> 10^6$), we show a set of models in which -200 km s$^{-1} \leqslant V_\theta \leqslant 200$ km s^{-1} and -180 km s$^{-1} \leqslant V_\theta \leqslant 180$ km s^{-1} for M31 and M33, respectively, and -200 km s$^{-1} \leqslant V_\phi \leqslant 200$ km s^{-1} and -180 km s$^{-1} \leqslant V_\phi \leqslant 180$ km s^{-1} for M31 and M33, respectively. This set of models is chosen, because a larger fraction of models can better reproduce the observed location of the HI gas: other sets of models with larger V_θ and V_ϕ can not well reproduce the observations. It should be noted here that the adopted upper value of $V_\theta = 180$ km s^{-1} is well consistent with the transverse motion suggested by Brunthaler et al. (2005, B05) who investigated the proper motion of M33. The ranges of the *present* 3D velocities (V_X, V_Y,V_Z,) for M31 and M33 in this set of models are summarized in the Table 1.

2.2 Disk evolution

In test particle simulations, M33 is assumed to have an exponential disk composed of gas and stars. Previous observations showed that the size of the HI disk (r_g) is at least twice more extended than that of the stellar one (r_s) in M33 (e.g., Corbelli et al. 1989). We thus consider that (1) $r_s = 10$ kpc and (2) $r_g/r_s > 2$. For all models, the observed present inclination angle of $56°$ and the position one of $23°$ (e.g., van den Bergh 2000) are adopted for initial disk inclinations ($T = -9.2$ Gyr). The initial rotational velocity of each particle is derived from M_{M33} and the positions with respect to the center of M33. Although the final inclination angles of the stellar disk ($T = 0$ Gyr) are similar to the initial ones ($T = -9.2$ Gyr), the final gas disk ($T = 0$ Gyr) shows different inclination angles from those of the initial one owing to the past M31-M33 interaction. The derived different distributions of gas and stars, however, are not inconsistent with

Table 2. Initial positions and velocities of M31 and M33 (i.e., 9.2 Gyr ago) adopted for the orbital evolution in the selected two successful models.

Model	(X, Y, Z) for M31 [a]	(V_X, V_Y, V_Z) for M31 [b]	(X, Y, Z) for M33	(V_X, V_Y, V_Z) for M33
M1	(-1682, 1633, 780)	(131, -100, -111)	(-1800, 1617, 677)	(180, 85, -21)
M2	(-1046, 398, -1196)	(57, 32, 83)	(-1027, 247, -1196)	(-24, -102, -29)

[a] Positions are given in units of kpc.
[b] Velocities are given in units of km s^{-1}.

Figure 2. Time evolution of distances between M31-M33 (thick solid), M31-Galaxy (thin solid), and M33-Galaxy (dotted) for the last ~ 9 Gyr in the model M1 (upper) and M2 (lower). Here the time $T = -9.2$ Gyr and $T = 0$ Gyr represent initial and final (i.e., now) state of the model, respectively.

observations by Corbelli & Schneider (1997) which shows a wap only in the gaseous component.

For each model, we investigate whether the final (i.e., T=0, now) distribution of stripped gas particles can be similar to the observed one of the HI bridge. We try to find "successful models" in which the following three conditions are satisfied: (1) at most 50 % of initial gas can be stripped to from HI streams, (2) the distribution of stripped particles can be similar to the observed HI bridge on the (α, δ) plane, where α and δ are right ascension and declination, respectively, and (3) the stellar disk of M33 can not be stripped at all. The above conditions (1) and (2) imply that the tidal radius (r_t) of M33 with respect to M31 should be $r_s \leqslant r_t \leqslant r_g$ throughout the orbital evolution of M33. The condition (3) is essentially similar to that adopted by Loeb et al. (2005) for constraining orbital evolution of M31 and M33.

In order to investigate whether the above condition (2) is satisfied in a quantitatively manner, we adopt the following procedure. We firstly designate rectangular regions with the number of N_r on the (α, δ) plane so that the rectangular regions can cover the observed location of the HI

bridge (BT04). Fig. 1 shows the 7 rectangular regions used for investigating the successful models in the present study. We then investigate whether gaseous particle can be within rectangular regions. If a region includes at least one gaseous particle, then $f_{f,i} = 1$ $(i = 1, N_r)$ is allocated: otherwise $f_{f,i} = 0$. We estimate the following quantity F_f:

$$F_f = \frac{1}{N_r} \sum_{i=1}^{N_r} f_{f,i} \tag{2}$$

If F_f exceeds a threshold value of $F_{f,th}$ in a model, we regard the model as satisfying the above condition (2).

We set $F_{f,th}$ to be 0.7 and thereby derive the present 3D velocities of M31 and M33 for the successful models. This is because we consider that the successful models explain both the HI bridge and the gas in the northern part of the M31 halo (Braun & Thilker 2004): most rectangular regions need to contain particles in the successful models. We show the results of the models with $r_g/r_s = 3.5$ in the present study: models with smaller r_g/r_s (e.g., 2.0) do not show the formation of the HI bridge. It is found that only 12 models among 160000 can satisfy all of the above three conditions for $F_{f,th} = 0.7$: the number of successful models is 293 for $F_{f,th} = 0.4$.

For these successful models, we rerun test particle simulations with particle numbers of 20000 to investigate the details of the distributions of stripped gaseous particles on the α-δ plane. We choose only two successful models to describe the results in the present study. The initial positions and velocities of these two models (M1 and M2) are shown in the Table 2. Fig. 1 clearly demonstrates that the successful model M1 can really reproduce the HI bridge between M31 and M33: the detailed explanations for Fig. 1 are given in §3.

The present model is more idealized (e.g., point-mass model for M33) so that the selection of best possible orbital models can be feasible. If we adopt a more realistic model for the distribution of the dark matter halo of M33, the results of the present simulations could be changed. For example, if we adopt the radial density profile predicted from hierarchical clustering scenarios of galaxy formation (the "NFW" profile ;Navarro, Frenk & White 1996), the outer part of the M33 disk is more strongly influenced by the M31 tidal field owing to the weaker gravity of the halo in comparison with the present point-mass M33 model. Although this more efficient stripping in the model with the NFW profile would increase the total mass of the stripped HI gas from M33, the selection process of the best possible model(s) would not depend so strongly on the choice of the halo profile: this is because the orbit of M33 (in particular, the pericenter distance) with respect to M31 is the most important parameter for tidal stripping of the HI gas.
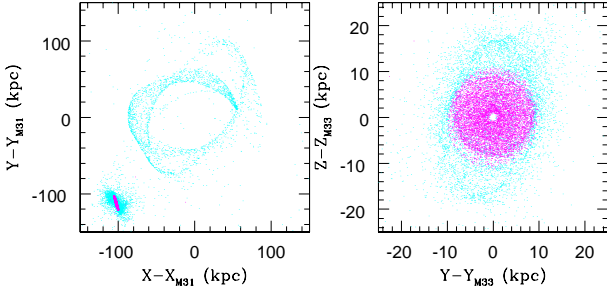
Figure 3. Distributions of stellar (magenta) and gaseous (cyan) particles projected onto the X-Y plane (left) and the Y-Z one (right) in the model M1. The center of frame in the left panel with a larger field of view is coincident with that of M31 so that the tidal stream(s) can be more clearly seen. The center of frame in the right panel with a smaller field of view is coincident with that of M33 so that inner distributions of gas and stars can be more clearly seen.

3   RESULTS

Fig. 2 shows that (i) M33 is tightly bounded by M31 for the last ~ 9 Gyr, (ii) the pericenter distance ($r_{\rm p}$) between M31 and M33 at the last strong interaction about 8.4 Gyr ago is 92 kpc, and (iii) both M31 and M33 are now approaching the Galaxy for the model M1. Since the orbit of M33 with respect to M31 is significantly elongated with the orbital eccentricity (e) of 0.6, the last interaction means the first one. The last tidal interaction about 8.4 Gyr ago is responsible for tidal stripping of gas and the resultant formation of a HI bridge in this model M1: the observed HI bridge could be be a relic of an ancient tidal interaction between M31 and M33.

Fig. 3 shows that although a significant fraction ($\sim 42\%$) of gas can be stripped from M33 owing to the M31-M33 interaction, the stellar disk of M33 can not be strongly disturbed in the model M1. The gas disk of M33, however, appears to show a more elongated morphology with some signs of disturbance. The gas disk can be significantly more extended than the stellar one even after the strong tidal interaction with M31 during the last 9 Gyr. The stripped gas can form a tidal stream around M31, which appears to have a weak physical connection with M33 if it is projected onto the X-Y plane. Clearly gas particles in the stream are rotating around M31 and thus show systematic rotation with respect to M31.

As shown in Fig. 1, the tidal stream appears to be a giant filament or a bridge-like structure if it is projected onto the α-δ plane. The model shows that the stream extends to the north-east part of M31, which is consistent with the observation (BT04). The model predicts that there can be no thin tidal streams (e.g., leading tidal tails) in the southern part of of M33. Figs 1 and 3 thus suggest that the observed HI bridge is actually a tidal stream around M31 viewed edge-on.

Morphological properties of the simulated HI bridges can be different between the 12 successful models. Fig. 4 shows the results of the model M2, in which M33 can very strongly interact with M31 with small $r_{\rm p}$ of 67 kpc and $e = 0.6$ for the first time around 4.2 Gyr ago (see also Fig. 2 for the orbital evolution). Owing to the stronger tidal interaction, the final distribution of gas particles on the α-δ
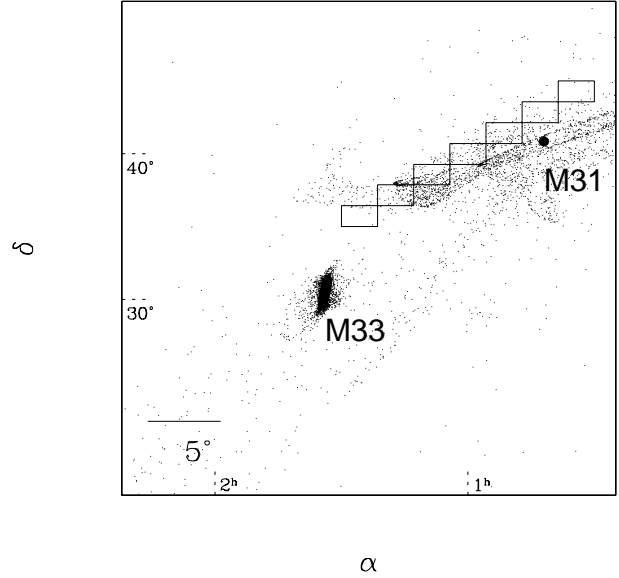

Figure 4. The same as Fig. 1 but for the model M2.

plane appears to be more dispersed. However, it is clear that the HI bridge is well reproduced in this model M2. One of interesting results in this model is that some fraction of the stripped gas appear to be more uniformly distributed in the surrounding region of M31.

Thus, these results clearly demonstrate that the observed HI bridge can be a tidal stream formed from the ancient tidal interaction between M31 and M33 possibly about 4-8 Gyr ago. The present models, however, can not provide a robust prediction on *the exact epoch* when the HI bridge was formed around M31. Owing to the adopted test particle simulations *without self-gravity of gas*, the observed gaseous warp of M33 can not be formed in the present models even if M33 strongly interacts with M31. Given that previous simulations demonstrated the formation of warps in interacting galaxies (e.g., Tsuchiya 2002), it is highly likely that the past M31-M33 tidal interaction can also induce the formation of gaseous warps in the outer part of M33.

We confirm that if the gas disk of M33 is more extended ($r_{\rm g}/r_{\rm s} \sim 3$) *when M33 first interacts with M31*, a bridge-like HI structure can be formed for a range of orbits of M31 and M33: the M33 gas disk at the epoch of the first M31-M33 interaction could be more extended and more massive than the present one. The total mass within the bridge depends on the initial gas mass of M33. Therefore, the observed column density of the HI bridge can give some constraints on the initial gas mass of M33, if the HI bridge is really formed from the M31-M33 interaction. Column densities and kinematics of HI streams need to be investigated in fully self-consistent simulations with gaseous self-gravity, because gaseous self-gravity can play a key role in forming local high-density region (e.g., Bekki et al. 2005a). Our future more sophisticated numerical simulations with gaseous self-gravity will allow us to discuss the observed column density and kinematics of the HI bridge in a quantitative manner.

4 DISCUSSION AND CONCLUSIONS

Although the present study has presented a scenario that the observed apparent HI bridge between M31 and M33 is a tidal stream of HI gas around M31 formed from the past M31-M33 interaction, this scenario would be only one of several possible scenarios. For example, BT04 suggested that the observed bridge can be a "cosmic web" which extends between massive galaxies as predicted in previous numerical simulations on structure formation. It would be also possible that the bridge is a tidal stream originating not from M33 but from other gas-rich dwarfs that may have already been destroyed by the strong tidal field of M31. If fully self-consistent hydrodynamical simulations for the bridge formation in our future studies can also reproduce the observed sharp HI edge and outer HI warps in M33 (e.g., Corbelli & Salpeter 1993; Corbelli et al. 1997), then the present interaction scenario can be regarded as more realistic and reasonable.

Ibata et al. (2007) have recently found an extended metal-poor stellar halo around M33 in the deep photometric survey of M31, though the projected distribution of the halo is not so clear owing to the very limited spatial extent of the survey. If the stellar halo of M33 has a relatively homogeneous spatial distribution with no signs of disturbance and extends more than 35 kpc from the center of M33, then M33 is highly unlikely to have lost HI gas initially within 35 kpc: the present tidal interaction scenario needs to be dramatically modified. It would be possible that the observed outer metal-poor halo of M33 can be the very outer part of the M31 stellar halo. Future kinematical studies of metal-poor stars around M33, which can confirm that the stars belong to M33 rather than to M31, will enable us to discuss how far the M33 stellar halo extends and thereby assess the viability of the present tidal interaction scenario.

The present models have shown that HI gas clouds originating from M33 can be located in tidal streams within ~ 100 kpc of M31 and show systematic rotation with respect to M31. One of implications from this result is that at least some of the observed HVCs around M31 (e.g., West-meier et al. 2007) can originate from M33. Metallicities of the M31 HVCs originating from M33 may well be as small as those of HI gas in the outer part of the gas disk in M33. Also the HVCs from M33 can have systematic rotation with the amplitude significantly smaller than that of the M31 disk ($V_c \sim 250$ km s^{-1}). Thus future observational studies on chemical abundances and kinematical propertied of HVCs will help us to reveal the M31 HVCs originating from M33.

Although the present gas-rich late-type disk galaxies are observed to have extended HI disks (e.g., Broeils & van Woerden 1994), it remains observationally unclear how and when the extended HI disks were formed. The present model M1 (with the first M31-M33 interaction about 8 Gyr ago) would not be reasonable, if the extended HI disk in M33 was formed relatively recently (4-5 Gyr ago). It should be thus stressed that the viability of the present scenario for the origin of the M31-M33 HI bridge would depend on whether *M33 had already developed its extended HI disk before it experienced the first tidal interaction with M31.*

Loeb et al. (2005) proposed a proper motion amplitude of 100 ± 20 km s^{-1} form M31 based on orbital models of M31 and M33 and on the observed proper motion of M33 by B05.

Recently van der Marel and Guhathakurta (2007) have investigated line-of-sight velocities of the seventeen M31 satellite galaxies in order to derive the M31 transverse velocity. They have found that the Galactocentric tangential velocity of M31 is highly likely to be less than 56 km s^{-1} and suggested that M31 and M33 is in a tightly bounded system. These results appear to be consistent with the present tidal interaction scenario for the HI bridge. As shown in the present study, the observed location of the HI bridge alone can not allow us to provide very precise predictions on the present 3D velocities of M31 and M33. We plan to use the observed kinematical data sets for the HI bridge in order to give much stronger constraints on the 3D orbits of M31 and M33 by comparing the observations with more sophisticated numerical simulations.

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